

ROMERIN: A Modular Climber Robot for Infrastructure Inspection

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Abstract: This paper presents some of the developments made in the construction of a modular climbing robot for infrastructure inspection. The development and optimization of independent vacuum generator systems for each leg is presented, with the flow-rate taking priority over the relative pressure. It also describes the general robot structure, as well as the initial mathematical models required for the development of a control system based on an biomimetic organic model. Finally, it is highlighted the use of simulators to help the iterative design process of a strongly mechatronic system. Some of the obtained results have been experimentally validated.

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1. INTRODUCTION

Over the past half-century, the growth of civil infrastructure has been particularly intense. Consequently, these same facilities require an ever-increasing expense for their inspection, replacement, or, if necessary, disassembly. The analysis carried out by the European consortium SPARC (euRobotics) emphasizes that in the coming years this task will be increasingly important and relevant and foresees that the role that robots will play in maintenance, inspection and dismantling will be critical. Moreover, inspection is a particularly structured repetitive task, that requires permanent attention during the operation, and in many cases it involves placing the human operator in risk situations. That is why robotics is revealed as a technology of direct application.

In fact, if you look at the reports issued by IFR, JIRA, euRobotics, they all show the explosion that is taking place in the field robotics market, and in particular the drones, both UAVs, UUV and UGV. The number of service robots, mainly driven by drones, has increased by 25% in the last year, and the number of autonomous vehicles in a non-manufacturing environment, in one year has increased by 51%.

The robotic system (ROMERIN) presented in this article, aims to design a climbing robot that can move on vertical surfaces and even ceilings. Unlike some of the existing developments, the robot uses a turbine per each suction cup to generate the required negative pressure. The use of a turbine as opposed to a pump, has as main advantage the great flow and as consequence its acceptable adhesion capacity even in the presence of cracks or defects or on rough surfaces. The fact that the suction is generated independently in each leg avoids the effect of pressure loss in the entire robot when one of the suction cups is placed in an area with excessive air loss (Schmidt, 2013b). Finally, and no less importantly, this

structure allows the development of a modular robot in which one or two legs can form an electromechanically self-contained unit.

There are currently designs of climbing robots for the purpose of carrying out specific work on certain infrastructures. These tasks may be risky for human operators or may require a high level of precision, for example (Schmidt, 2013):

- Inspection of wind generators in operation
- Cleaning of windows in large buildings
- Analysis of aircraft fuselages, and ship hulls
- Revision, dismantling and dismantling of nuclear power plants
- Inspection of large buildings, tunnels, cooling towers and large infrastructures

In the past few years a considerable number of climbing robots have been developed. A good summary of the technologies involved and the different approaches can be found in (Miripour, 2010). These robots could be clearly differentiated based on two principles: the type of locomotion on which they are based and the adhesion system used. Most climbing robots are based either on the use of vacuum systems, or magnetism in the case of working over metallic structures. The recent proliferation of electrostatic systems based on the imitation of gecko (Kasem, 2015) or microspines which employs arrays of miniature spines that catch on surface asperities (Kalouche 2014) or dry adhesives is noteworthy. (Xu 2018). Similar to our development is of special interest RVC (Reconfigurable Vertical Climber), a modular robot that uses permanent magnets in pads for the inspection of complex ferromagnetic structures (Peters, 2010). Another strong trend that exists today and that has been successfully applied to window

cleaning robots is the use of a body adhesion system (usually suction by means of turbines or regenerative vacuum pumps) and an independent locomotion system such as wheels that passively maintain contact with the surface.



Fig 1. Hexapod prototype stuck to a rough gypsum wall with four of its six legs.

As mentioned above, the ultimate purpose of ROMERIN is the development of a modular scalar robot with the specific application of performing inspection tasks in infrastructure. However, there is no knowledge of climbing robots with the generation of vacuum per leg, without umbilical cord, and what is more interesting, modular. The modularity proposed in this project, although it entails the complexity of developing a control that will work with a variable arrangement of elements, has a very relevant practical purpose, and is the possibility of increasing the load capacity and gripping force according to the type of application, the autonomy and the useful load to be carried.

The greatest complexity lies in dealing with a control that will necessarily be Model-Based, and that will have to combine the strategies for generating cyclic patterns with the corrections required due to the lack of grip, posture and terrain configuration.

The project encompasses several phases, including the design, development and construction of a demonstrator robot, and tests in real environments, such as tunnel inspection tasks and inspection of nuclear power plant cooling towers. It should be pointed out that these inspection tasks, given the conditions of the environment and the inspection system required, cannot be performed by means of UAVs (due to their limited load capacity, inherently unstable nature of the flight system they use, and accident risk) or strictly terrestrial vehicles (limited by the type of terrain on which they can move).

For this reason, the development has been structured in a staggered way, starting from a prototype based on a commercial platform and making intensive use of current dynamic simulation systems. Afterwards, the development of our own modular system will be addressed.

For this reason, we have modified a robot marketed by the company XYZ Robot (XYZ Bolide Y-01). The mechatronic modifications have been made to this model in order to allow it to adhere to the walls (Fig. 1). This article shows some of the advances in the suction cup design the modeling and optimization of the gripping system.

The article is organized as follows. First, the first prototype is described in a general way. Next, part of the theoretical and finite element optimization carried out to achieve the greatest efficiency in the vacuum generation system is presented, as well as some of the experiments that have allowed to validate and optimize it. Subsequently, the mathematical model is described, which allows, in real time, to obtain an approximation of the gripping forces in the suction cups for a hyperstatic contact with a variable number of legs. Finally, the results are validated by dynamic simulation.

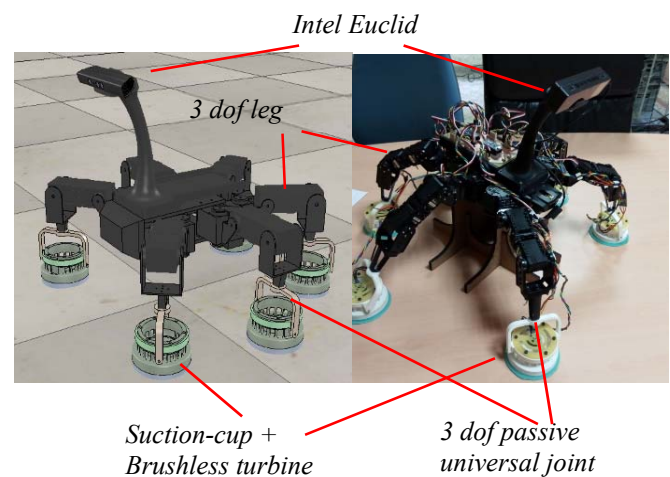


Fig 2. VREP model and real prototype.

2. ROMERIN DESCRIPTION

The main characteristics of the prototype are the following. It consists of 6 legs with three active degrees of freedom, motorized with smart servos of a maximum torque of 25 Kg-cm. At the end of each leg are the suction cups that are attached by a ZYZ joint that cross the articulation axis at a point placed in the space at 2 cm from the surface (Fig. 2). The aim is to minimize the emergence of torques on the suction cups, given how harmful they are to a stable grip. The suction cups are equipped with a BSC-ESC that controls the brushless motor that powers the vacuum turbine (Turnigy Multistar 1704-2300Kv 12 Pole Multirotor Outrunner V2). They also contain a pressure sensor (BMP280) and an infrared distance sensor (TCRT5000) with a small range (1-2 cm) that allows to detect the presence or not of a surface (Figure 3).

In the body of the robot is the MCU card based on the microcontroller ATmega1280. The MCU communicates with a Trinket Pro 5V for the control of the suction cups, with the 18 motors of the legs and with the Intel Euclid that is the brain and the main sensor system of the robot. This component allows to obtain an RGBD image of the environment, to process it, and to communicate with external components,

since it contains a powerful processor (Intel Atom x7-z8700) with Ubuntu 16.04 and ROS. The robot is powered by a LiPo 3S 5500mA battery.

Once the robot is described, we focus on the adhesion system, and on vacuum generation.

3. VACUUM GENERATION

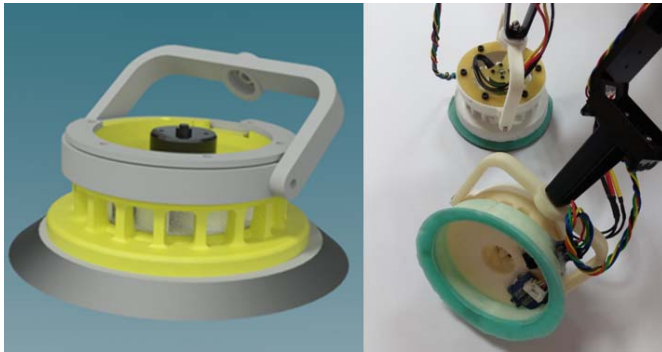


Fig. 3. 3D model of the per-leg vacuum system and suction cup (left), and the built prototypes. The sensors included into the suction cup are shown in the right picture.

At the end of each leg a suction cup is attached to stick to a wall or any other non-horizontal surface (Fig. 3). To create the needed vacuum, every suction cup is equipped with its own turbine and motor. The turbine as well as the stator around it, are printed with a 3D printer, therefore it is easy to modify the design of the system to find the most efficient geometry. This means that the turbines' design must be optimized so that the pressure will be as low as possible. This way the rotational speed can be limited to lessen the wattage needed to power them.

By looking at the vacuum cleaner turbine designs, a first model was created with the dimensions of the stator and the designed suction cup in mind. The diameter and the height of the turbine can still be adjusted but because the legs of the crawler robot are close together, the design cannot be very too wide or otherwise the suction cups would overlap when walking.

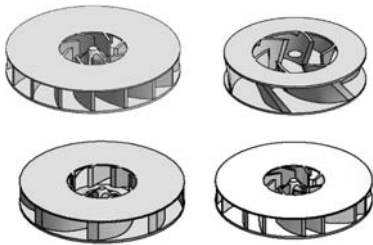


Fig. 4. Some of the turbines tested. The number of blades, their length, inclination, height, etc. are examples of the parameters that have been modified.

This first turbine design had ten blades, a diameter of 40 mm and a total height to 10.8 mm. The blades are curved backwards, and they are also curved going from the front plate to the back plate. Starting from this design, a set of modifications were tested in order to improve the turbine (Fig. 4). This include either the dimensions of the turbine, the

amount of blades or the shape of the blades. The initial turbine has an efficient coefficient of 1.53 (mbar/Watt), at the end of the optimization process we achieved 1.8, that is a 17% more.

3.1 ANSYS FLUENT simulation for optimization

To find these improvements without always having to reprint the design and test it, the program Ansys Fluent was used. This method allows the user to test several designs of the turbine to compare them to each other and find the most efficient ones in terms of pressure.

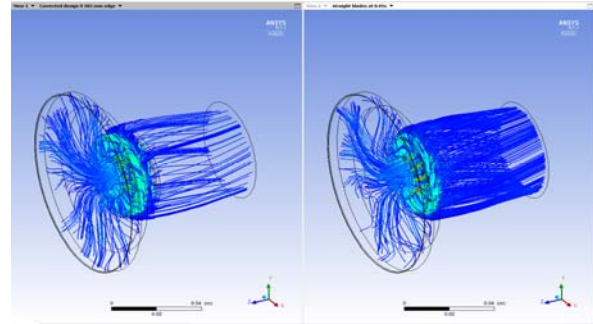


Fig. 5. Graphical representation of flow lines for two different turbines, inclined blades (left) vs. straight blades (right)

It is also possible to improve the design thanks to the detailed information that the program can generate showing pressures and flows impossible to measure or visualize experimentally. From an academic point of view, it also allows us to understand some of the effects that cause the final pressure to behave in one way or another, in a system of these characteristics. For example, both in simulation and experimentally it has been proven that the pressure is lower with straight than inclined blades (with respect to the rotation axis). When visualizing the flow lines, the reason for this behavior is obtained. If the blade is curved, the airflow is pushed against the back plate and that diminishes the velocity (Fig. 5). This is not the case when the blades are straight, where the streamlines concentrate in the middle of the turbine and exit towards the stator. Result indicate better pressure with straight blades (21% increase)

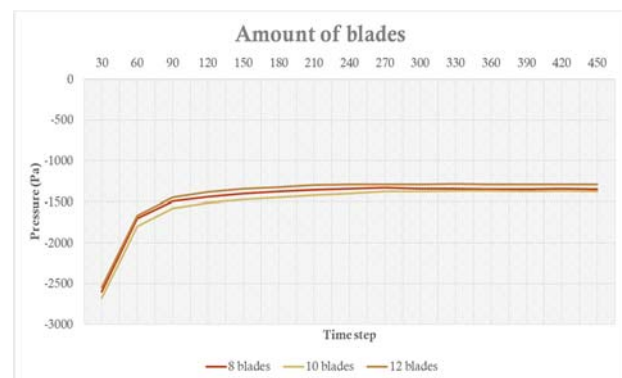


Figure 6. The number of turbine blades have no significant impact on the Pressure/power consumption.

Another surprising result given by the simulator is the practically null effect that the number of blades (from 8 to 12) has on the performance and the relative pressure achieved. Figure 6 shows the evolution over time of the pressure.

3.2 Experimental optimization

Given the characteristics of the simulated system, it is necessary to proceed to an experimental validation of the results. Obviously the number of experiments carried out is much lower. It is interesting to observe how experimentally it is verified that the results produced by the simulation were correct. Figure 7 shows the best behaviour of the straight blades against the inclined ones.

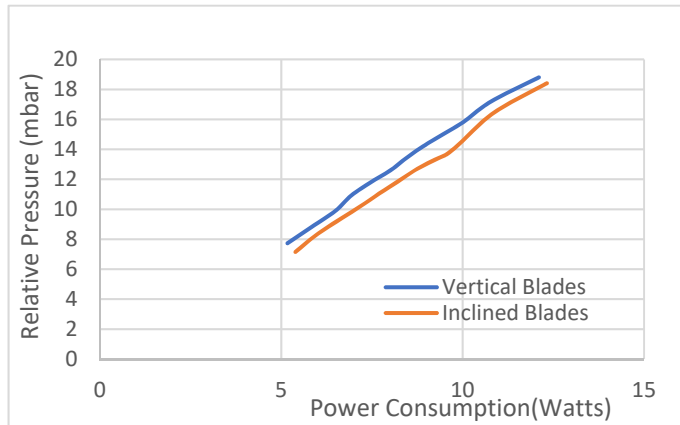


Fig. 7. Experimental validation of the Ansys Fluent simulation conclusion. The vertical blades are more effective than the inclined ones.

In addition, the experiments provide real values of consumption and efficiency as shown in Table 1. The data shows that one suction cup was able to produce 15 Newtons with a Consumption of only 12 Watts.

Table 1. Experimental results of one of the experiments.

Intensity	RPM	Abs. Press (mbar)	Rel Pres (mbar)	Power (Watts)	Motor Performance (rel Press/Watt)	Force (N)
0,48	15090	939,28	8,38	5,28	1,587	5,94
0,54	16200	937,85	9,81	5,94	1,652	6,95
0,59	17100	936,85	10,81	6,49	1,666	7,66
0,64	17940	935,73	11,93	7,04	1,695	8,46
0,69	18600	934,77	12,89	7,59	1,698	9,14
0,73	19260	933,74	13,92	8,03	1,733	9,87
0,78	19860	933,23	14,43	8,58	1,682	10,23
0,81	20370	931,71	15,95	8,91	1,790	11,31
0,85	20820	930,81	16,85	9,35	1,802	11,94
0,9	21360	929,76	17,9	9,9	1,808	12,69
0,98	22320	928,19	19,47	10,78	1,806	13,80
1,13	23340	926,37	21,29	12,43	1,713	15,09

More than 40 different tests have been carried out to obtain a sufficiently efficient vacuum system.

4. ROBOT MODELS

4.1 VREP Dynamic modelling

In order to test and verify that the implementations are safe, a model is built in the V-REP simulator (Virtual Robot Experimentation Platform). Developed by Coppelia Robotics, this is one of the most powerful and versatile simulators available today. It has compatibility with a great variety of programming languages, such as C/C++, Python, Matlab, Lua or Java. In addition, it allows you to control each object of the simulation individually through a multitude of tools such as ROS nodes, plugins or scripts, among others.

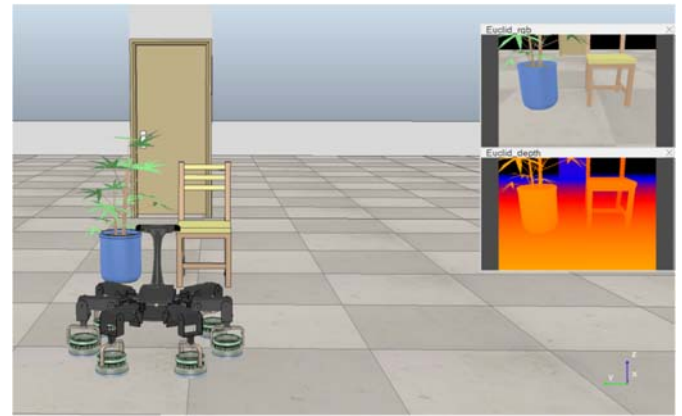


Fig. 8. The robot simulated in VREP showing the RGB-D capture of the virtual Intel Euclid.

Among other things, VREP supports dynamic simulation of the robot. This includes the possibility to implement motor controllers, with saturations, PIDs, maximum speeds etc. It is also possible, among other things, to simulate the effect of a suction cup, as well as the friction of the grip, and to log the reaction forces. It is also capable of simulating complex sensors such as an RGB-D camera or a laser. Figure X shows the ROMERIN model built as well as the capture made by the simulated EUCLID that has been modeled in VREP based on another sensor (Kinect).

Although it is basically used to test the different locomotion strategies, in this case the VREP model will validate the mathematical model explained below (Fig. 8).

This model is considered essential in order to advance in the type of biomimetic control we plan to implement.

4.2 Mathematical model of contact forces

A critical aspect to control the robot while climbing is to ensure that normal and shear forces at the suction cup do not exceed certain limits during movement, given the risk of loss of grip (Ko, 2017). In our case the problem is even more complex given the possibility of having a number of contact points that make the system hyperstatic. In principle to solve the problem it would be necessary to consider the elastic

characteristics of the robot limbs and motors, that would make the system too complex to be included in the control loop of the robot. Therefore we look for a simplified mathematical model, faithful enough to be able to decide which leg to release, and where to place it, as well as to inform about the convenience of moving the center of gravity of the robot in one direction or another.

To obtain the static model of the reaction forces in the suction cups, we have decided to use a simplified dynamic model given the hyperstatic nature of the problem. The simplifying hypotheses that have been assumed are the following:

- Robot legs are considered rigid, non-deformable.
- In the suction cups, due to the universal joint that holds them, only reactive forces will be produced, not torques.
- In order to solve the hyperstaticity, it will be assumed that the contact points are elastic with a constant K .

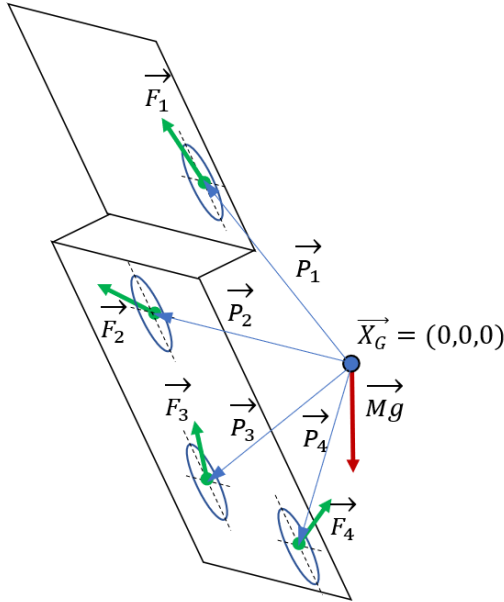


Fig. 9. elements used in the reactions force dynamic model.

With these assumptions, an approximation of the load distribution in each suction cup can be obtained in a relatively simple way. In the absence of external forces, the robot center of gravity is located at point \vec{X}_G initially zero (Figure 1).

As a consequence of the gravity and the reactions in the points of support, the center of gravity moves and rotates according to ${}^0T_R = ({}^0R_R, {}^0\vec{P}_R)$ where ${}^0R_R \in SO(3)$ and ${}^0\vec{P}_R \in \mathbb{R}^3$ are the orientation matrix and the position vector of the new position of the center of gravity with respect to the initial (Figure 10).

With these premises, for the system to be stable, the equations of static equilibrium must be fulfilled:

$$\begin{aligned} \sum \vec{F}_i + M\vec{g} &= 0 \\ \sum \vec{\tau}_i &= 0 \end{aligned} \quad \begin{matrix} (1) \\ (2) \end{matrix}$$

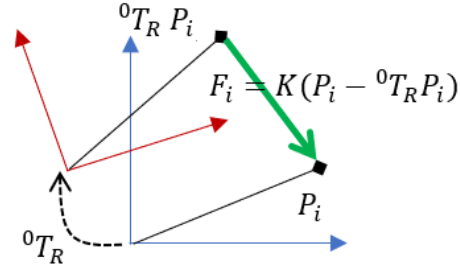


Fig. 10. Reaction force computation as an elastic force due to the CG displacement.

According to these hypotheses, the reactive force \vec{F}_i in each suction cup would therefore be obtained from:

$$\vec{F}_i = K(\vec{P}_i - {}^0T_R \vec{P}_i) = K(\vec{P}_i - {}^0R_R \vec{P}_i - {}^0\vec{P}_R) \quad (3)$$

$$\vec{F}_i = K((I - {}^0R_R)\vec{P}_i - {}^0\vec{P}_R) \quad (4)$$

On the other hand, applying the equation of equilibrium of moments:

$$\sum \vec{\tau}_i = \sum \vec{F}_i \times ({}^0R_R \vec{P}_i + {}^0\vec{P}_R) + M\vec{g} \times {}^0\vec{P}_R = 0 \quad (5)$$

$$\sum \vec{F}_i \times ({}^0R_R \vec{P}_i) + (\sum \vec{F}_i + M\vec{g}) \times {}^0\vec{P}_R = 0 \quad (6)$$

That by the equation of forces can be simplified in

$$\sum \vec{F}_i \times ({}^0R_R \vec{P}_i) = 0 \quad (7)$$

$$\sum K((I - {}^0R_R)\vec{P}_i - {}^0\vec{P}_R) \times ({}^0R_R \vec{P}_i) = 0 \quad (8)$$

$$\sum K(\vec{P}_i - {}^0R_R) \times ({}^0R_R \vec{P}_i) = 0 \quad (9)$$

Therefore, parameterizing 0T_R , by means of the spatial location vector of the displacement and rotation of the center of gravity $\vec{x} = (x, y, z, \alpha, \beta, \gamma)$, and as consequence:

$${}^0\vec{P}_R = \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \quad {}^0R_R = \text{RotX}(\alpha)\text{RotY}(\beta)\text{RotZ}(\gamma) \quad (10)$$

$${}^0R_R = \begin{pmatrix} c\beta c\gamma & -c\beta s\gamma & s\beta \\ sas\beta c\gamma + cas\gamma & -sas\beta s\gamma + cac\gamma & -sac\beta \\ -cas\beta c\gamma + sas\gamma & cas\beta s\gamma + sac\gamma & cac\beta \end{pmatrix} \quad (11)$$

As a result, we have a system of six non-linear equations with six unknown variables that we must solve. Newton's method is one of the most popular numerical methods used to solve for the equation $f(x) = 0$. We know from Linear Algebra that we can take systems of equations and express those systems in the form of matrices and vectors. With this in mind, we can express the nonlinear system as a matrix with a corresponding vector. Thus, applying the Newton's method, the following equation is derived:

$$x^{(k)} = x^{(k+1)} - J(x^{(k+1)})^{-1} F(x^{(k+1)}) \quad (12)$$

where $F : \mathbb{R}^6 \rightarrow \mathbb{R}^6$ is the function that maps $(x, y, z, \alpha, \beta, \gamma)$ and $(\Sigma F_x, \Sigma F_y, \Sigma F_z, \Sigma \tau_x, \Sigma \tau_y, \Sigma \tau_z)$, and $J(x)$ is the Jacobian matrix of F .

4.3 Validation of the mathematical model

A first validation of the used model comes from VREP's ability to easily extract forces and torques at any point on the robot. VREP has the possibility of using several dynamic motors,

including Bullet, ODE, Vortex and Newton. The results are therefore good enough to validate the model given the application that is wanted. Figure 11 shows graphically the calculated force vectors and compares them with those obtained by the simulator.

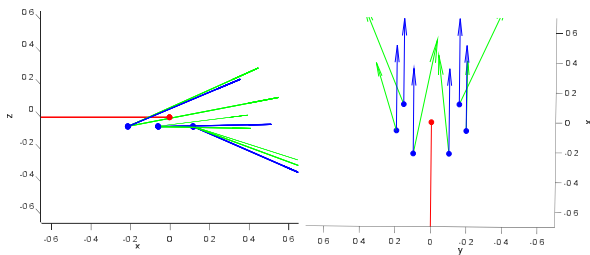


Fig. 11 Force vectors calculated in blue (plan view and elevation), starting from the contact points of the suction cups. Those obtained by the simulator are shown in green. In red the gravity vector departing from the correspondent gravity center of the robot.

The most significant differences are found in the plane of the wall. This is because VREP simulates the motor controllers, and thus the forces the controllers exert to drive the joints to the set points. However, in the model the position of the legs is precise and ideal.

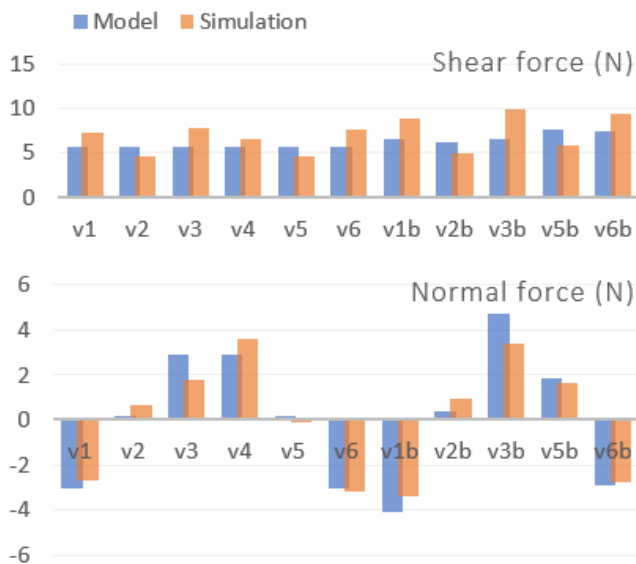


Fig. 12. Comparative between shear and normal forces between the mathematical model and the simulation.

Figure 12 shows the comparison between normal and tangential forces for each suction cup when the robot rests on six or five legs (suffix b). It is observed that the model is good enough to assess the risk of a suction cup becoming detached.

5. CONCLUSIONS

In this article we wished to present some of the advances and steps that have been made in the design of a modular climbing robot. Although it is an incipient work, the first results and

models are promising. Specifically, the use of simulators to facilitate design iterations and to validate working hypotheses has proved particularly effective.

6. ACKNOWLEDGMENTS

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